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eenens@astro.ugto.mx http://www.star.ucl.ac.uk/∼hsn/index.html

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Accepted Papers

On the periodic X-ray emission from the O7V star θ^1 Orionis C

J. Babel[1] and T. Montmerle[2]

[1] Institut für Astronomie und Astrophysik, Universität Kiel, Germany

[2] CEA, Service d'Astrophysique, Centre d'Etudes de Saclay, France

The O7V star θ^1 Orionis C was found very recently to present a strong periodic variation of the X-ray emission (Gagné et al 1997) in agreement with the period determined from the variability of spectral lines (Stahl et al 1996). The authors suggested that the variations are caused by an oblique magnetic rotator with a large scale magnetic field modulating the wind

We make here the hypothesis of a dipolar magnetic field embedded in the radiation driven wind of θ^1 Orionis C and analyze the X-ray data in the framework of the magnetically confined wind shock model (hereafter MCWS) (Babel & Montmerle 1997). We obtain that both the *ROSAT* HRI count rate and the periodic variability of θ^1 Orionis C are quantitatively reproduced by the model, provided that the field has an intensity at the stellar surface of $B_* \simeq 300$ G. The variability is caused in large part by the circumstellar cooling disk (CD) predicted by the MCWS model. These results give a strong support to the magnetic origin of the variability of θ^1 Orionis C and make this star be the best candidate of a high-mass analogue to magnetic Bp stars.

Accepted by Astrophysical Journal Letters

Preprints from `Jacques.Babel@obs.unige.ch`

Helium absorption and emission towards Θ^1 Ori C

René D. Oudmaijer[1], Janet E. Drew[1], M. J. Barlow[2], I. A. Crawford[2], & D. Proga[1]

[1] Imperial College of Science, Technology and Medicine, Blackett Laboratory, Prince Consort Road, London, SW7 2BZ, U.K.

[2] Department of Physics & Astronomy, University College London, Gower Street, London WC1E 6BT,U.K.

The He I absorption and emission systems towards Θ^1Ori C, the exciting star of the Orion Nebula, are investigated. To this end, high resolution near-infrared long-slit spectra centred on the He I 1.083μm and Brγ lines and an ultra-high resolution (R $\sim 10^6$) spectrum of the optical He I 3889Å line have been obtained. These data are supplemented by blue high spectral resolution echelle observations of Θ^1Ori C and the other members of the Trapezium. Even at R $\sim 10^6$, the He I absorption profile, associated with foreground gas at a heliocentric velocity of +3 km s^{-1}, is very smooth suggesting a simple broadening mechanism and homogeneity. The combination of the He I 2^3S column density deduced from the 3889Å line with the non-detection of Brγ emission at the same velocities sets an upper limit on the electron density in this medium of 10^{10} m^{-3}. The He I 1.083 μm long-slit spectrum shows the familiar background nebular emission, while a second blueshifted component is visible off-star at the same velocities as the absorption. Several mechanisms to explain this emission are explored. We conclude that it is most probably emission formed behind and leaking through the absorbing gas layer. A clue to the origin of this emission is found in its spatial distribution: unlike the bright background nebular emission, the blueshifted component peaks symmetrically around the position of Θ^1Ori C, suggesting a physical association with the star. A possible model for the blueshifted emission is that it arises in a large scale, dense shock front, provoked in some way by the wind of Θ^1Ori C.

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For preprints, contact r.oudmaijer@ic.ac.uk

Coordinated ultraviolet and Hα spectroscopy of bright O-type stars

L. Kaper[1,2], H.F. Henrichs[2], A.W. Fullerton[3], H. Ando[4], K.S. Bjorkman[5], D.R. Gies[6], R. Hirata[7], E. Kambe[8], D. McDavid[9], J.S. Nichols[10]

[1] European Southern Observatory, Karl-Schwarzschild-Strasse 2, D–85748 Garching, Germany

[2] Astr. Inst., Univ. of Amsterdam, Netherlands

[3] Univ. Sternwarte, München, Germany

[4] Nat. Astr. Obs., Mitaka, Tokyo 181, Japan

[5] Univ. of Toledo, Ohio, U.S.A.

[6] Dept. Phys. and Astr., Georgia State Univ., Atlanta, U.S.A.

[7] Dept. of Astr., Kyoto Univ., Sakyo-ku, Kyoto 606-01, Japan

[8] Dept. of Geoscience, Nat. Def. Acad., Yokosuka, Kanagawa 239, Japan

[9] Limber Observatory, Texas, U.S.A.

[10] IPAC, CalTech, Pasadena, U.S.A.

As part of our search for the origin of stellar-wind variability, we have conducted simultaneous ultraviolet and Hα spectroscopy of a number of bright O stars. The observed changes in the Hα line occur at low velocity ($0 - 0.2v_\infty$) on timescales that are characteristic of the development and evolution of discrete absorption components (DACs) in UV resonance lines. In some cases, a direct relationship is found between the changes occuring in the Hα line and subsequent variations in the high-velocity

stellar wind. On the basis of this relationship, the appearance of a DAC in the UV resonance lines can be predicted from (ground-based) Hα observations.

These observations show that the stellar wind is variable down to regions close to or at the stellar surface. Since the timescales of the variations can be related to the rotation periods of the stars in our sample, we propose that a stellar magnetic field (which remains undetected) might play an important role in affecting the base of the stellar wind. The observed variations are interpreted in terms of corotating wind structures, similar to the Corotating Interaction Region (CIR) model proposed by Mullan (1986) and recently simulated by Cranmer & Owocki (1996).

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Wind variability of B supergiants. III. Corotating spiral structures in the stellar wind of HD 64760

A. W. Fullerton[1], D. L. Massa[2], R. K. Prinja[3], S. P. Owocki[4], and S. R. Cranmer[4,5]

[1] Universitäts-Sternwarte München, Scheinerstraße 1, D-81679 München, Germany

[2] Hughes STX, 7701 Greenbelt Road, Greenbelt, MD 20770, USA

[3] Dept. of Physics & Astronomy, University College London, Gower Street, London WC1E 6BT, UK

[4] Bartol Research Institute, University of Delaware, Newark, DE 19716–4793, USA

[5] Smithsonian Astrophysical Observatory, 60 Garden Street, Mail Stop 50, Cambridge, MA 02138, USA

Fourier analysis of two spectroscopic time series obtained with the *IUE* observatory confirm that the ultraviolet stellar wind profiles of HD 64760 (B0.5 Ib) are periodically variable. The periodic component consists of modulations that extend over most of the P Cygni absorption trough, and can frequently be traced through the emission lobe. The modulations coexist with variations due to the propagation of discrete absorption components, but there does not seem to be a direct link between these two types of variability.

In a long time series obtained in 1995 January during the *IUE* MEGA Campaign, the modulations in the P Cygni profiles of the Si III, Si IV, C IV, and N V resonance lines were dominated by two sinusoidal variations with semi-amplitudes between ∼5–10% of the continuum flux and periods of 1.202 ± 0.004 and 2.44 ± 0.04 days. The weak emission-lobe variability was predominantly due to the 2.4-day modulation. In the absorption trough, the ratio of the amplitude of the 1.2-day modulation to the amplitude of the 2.4-day modulation increased systematically as a function of ionization potential. For both periods, the distribution of the phase constant with position in the absorption trough exhibited a maximum near -710 km s^{-1} and decreased symmetrically toward larger and smaller velocities. There was a systematic decrease in the value of the maximum phase between Si IV and N V. Only the 2.4-day period was present in a shorter time series obtained in 1993 March, when its amplitude was nearly twice its 1995 value and it was more concentrated toward smaller velocities in the absorption trough. There is no clear evidence for phase bowing in the 1993 data.

Since the 2.4- and 1.2-day periods are approximately a half and a quarter of the estimated rotational period of HD 64760, respectively, we interpret the modulations in terms of 2 (1993) and 4 (1995) broad, corotating circumstellar structures that modulate the optical depth of the stellar wind. The bowed distribution of phase implies that the structures are azimuthally extended, probably spiral-shaped arms, and we develop a kinematic interpretation of the projected velocity associated with the phase turnover in terms of the degree of bending of the spirals. We derive a value for the exponent governing the radial expansion of the wind of $\beta \approx 1$, which is in good agreement with the canonical

value for smooth, spherically symmetric winds and suggests that the spiral structures are long-lived perturbations through which material flows. The systematic phase lag associated with higher ions suggests that they are preferentially located along the inner, trailing edge of the spiral, as expected if the structures are formed by the collision of fast and slow winds originating from equally-spaced longitudinal sectors of the stellar surface. Although a photospheric process is implicated in the origin of these structures, it is not clear that magnetic fields or nonradial pulsations could readily account for the switch between 2- and 4-equally spaced surface patches that evidently occurred between 1993 and 1995.

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`http://www.usm.uni-muenchen.de:8001/people/fullerton/pubs/preprints.html`

WR121 obscured by a dustcloud: the key to understanding occasional "eclipses" of "dusty" Wolf-Rayet stars ?

P.M. Veen[1], A.M. van Genderen[1], K.A. van der Hucht[2], A. Li[1], C. Sterken[3] and C. Dominik[1]

[1] Leiden Observatory, Postbox 9513, 2300 RA Leiden, The Netherlands

[2] Space Research Organization Netherlands, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands

[3] University of Brussels, Pleinlaan 2, 1050 Brussels, Belgium

We observed the Wolf-Rayet star WR 121 (= AS 320, WC9) coming out of a minimum with a depth of $0\overset{m}{.}8$ to its normal brightness in a dozen days. The nature of this event was analyzed by means of Walraven five-colour photometry. The colour changes are similar to those caused by interstellar dust. Hot dust is known to be formed continuously around this carbon-rich Wolf-Rayet star. Therefore, we suggest that the fading of WR 121 was caused by the temporary condensation of an optically thick line-of-sight dust cloud, comparable to what occurs around R Coronae Borealis stars.

We suggest that occasional "eclipses" shown by other "dusty" Wolf-Rayet stars (WR 113, WR 103) are also caused by such temporary condensing dust clouds. In addition, we present observations of a new "eclipse" of WR 103. This brightness dip was more shallow than the earlier "eclipses" and the star reddens during the descent. This also supports the model of a condensing dust cloud.

¿From modeling the shapes of the various "eclipses" we find that the condensation takes place at radii ranging from 80 to 800 $R_\odot$, i.e. between the stellar surface and the permanent dust shell that is inferred from the infrared excess. ¿From the colour changes we estimate the sizes of the particles in the clouds to be of order 0.1 μm and using the depth of the darkening we derive a dust mass condensation rate per column in the range of 3 – 20 10^{-10}kg m^{-2}s^{-1}. The dust mass flux per solid angle turns out to be comparable to that of the shell. Moreover, we find two possible trends within our small set of "eclipses": (1) the closer the condensation occurs to the star, the larger the dust mass flux is, and (2) the closer the condensation, the larger the particles are. These correlations are discussed within the framework of the model.

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Remarkable spectral variability in WR104 (WC9): Dust

condensation in a hostile environment?

Paul .A. Crowther

Department of Physics and Astronomy, University College London, Gower Street, London, WC1E 6BT, UK

We present new observations of the WC9 star WR104 (Ve 2-45), collected in 1996 July at the 2.5m Isaac Newton Telescope, which reveal unprecedented spectral and photometric variations. Relative to previous observations by Torres & Massey (1987) we find a simultaneous visual fading by $\sim$1.1 mag, plus the disappearance of high ionization spectral features (He II, C IV) with low ionization features (He I, C II) relatively unchanged. We interpret this behaviour as obscuration of the inner WR wind by a dust cloud condensation analogous to R CrB stars, and recently proposed to explain occasional eclipses in other WC9 stars (Veen et al. 1997). Non-LTE model calculations for the WC9 component (following Hillier 1990) indicate a cloud diameter $\gtrsim$60 $R_\odot$ (20 R_*) – far smaller than in R CrB stars – probably formed at a radius beyond 300$R_\odot$ (100R_*). We find the definite presence of a companion OB star which may facilitate the necessary conditions for dust formation via shocks.

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The "Mass Discrepancy" for Massive Stars: Tests of Models Using Spectroscopic Binaries

Valorie Burkholder[1], Philip Massey[2] and Nidia Morrell[3]

[1] Steward Observatory, University of Arizona, Tucson AZ 85719; vburkholder@as.arizona.edu

[2] KPNO, P. O. Box 26732, Tucson, AZ 85726-6732; massey@noao.edu

[3] Facultad de Ciencias Astronomicas y Geofisicas, Universidad Nacional de La Plata, Argentina; nidia@fcaglp.fcaglp.unlp.edu.ar

Stellar evolutionary models are often used to infer a star's mass via its luminosity, but empirical checks on the accuracy of the theoretical mass-luminosity relation for very massive stars have been lacking. This is of particular concern given that modern atmosphere models yield systematically smaller masses for massive stars than do evolutionary models, with the discrepancy a factor of two for Of stars. We attempt to resolve this mass discrepancy by obtaining new, high-resolution optical data on seven early-type spectroscopic binaries: V453 Cyg, HD 191201, V382 Cyg, Y Cyg, HD 206267, DH Cep, and AH Cep. Our study produces improved spectral substypes for the components of these systems, crucial for evaluating their luminosities and locations in the H-R diagram. Our radial velocity study utilizes a measuring method which explicitly accounts for the effects of pair-blending. We combine our new orbit solutions with existing data on inclinations and distances when available to compare the orbital masses with evolutionary models, and we find good agreement in all cases where the stars are non-interacting. (The components of V382 Cyg and DH Cep fill their Roche lobes, and in both cases we find masses substantially lower than the masses inferred from evolutionary tracks, suggesting that significant material has been lost rather than transferred. We confirm that this same trend exists for other systems drawn from the literature.) Our own data extends to only 15 $\mathcal{M}_\odot$, although photometric inclination determinations for HD 191201 and HD 206267 should prove possible, and will provide examples of higher mass systems. We briefly discuss suitable systems from the literature,

and conclude that orbit solutions provide good agreement with the evolutionary models to 25 $\mathcal{M}_{\odot}$. Beyond this, most known binaries either fill their Roche lobes or have other complications. We also discuss five systems for which our improved data and analysis failed to yield acceptable orbit solutions: EO Aur, IU Aur, V640 Mon (Plaskett's star), LY Aur, and 29 UW CMa all remained intractable, despite improved data.

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Time-series spectropolarimetry of the short-period Wolf-Rayet+O star binary CQ Cephei

Tim J. Harries[1] **and Ron W. Hilditch**[1]

[1] School of Physics & Astronomy, University of St. Andrews, North Haugh, St. Andrews, Fife, Scotland.

We present time-resolved, very precise linear spectropolarimetry of the short-period WR+O star binary CQ Cephei. We find that the N IV λ4058 line is the best spectral diagnostic of the WR orbital motion, and we derive a semi-amplitude $K_{\rm WR} = 290 \pm 1\,{\rm km\,s^{-1}}$ and a systemic velocity $\gamma = -72 \pm 1\,{\rm km\,s^{-1}}$. We identify an anti-phase spectral feature which we attribute to He I λ4143 absorption by the O star. A semi-amplitude of $360 \pm 18\,{\rm km\,s^{-1}}$ is found for the O star, giving a mass-ratio (WR:O) of 1.24 ± 0.06.

Spectropolarimetric measurements, combined with published photopolarimetry, enable a determination of the orbital inclination ($i = 82 \pm 0.5^{\circ}$). The emission-line polarization vectors allow us to separate the intrinsic and interstellar polarizations, and we find that the polarization attributable to scattering of the WR radiation in the expanding wind is small ($< 0.3\%$), but may be increasing towards the UV. We note that the inclinations derived from photometric analyses of eclipsing WR+O binaries are systematically lower than those computed from polarimetric measurements.

The light curves from Hiltner (1950) are analysed with LIGHT2 to confirm that the system is in a near-contact state. The resultant masses and astrophysical parameters show a normal main-sequence O star with a WR star that has parameters typical of the WN6 type. The distance modulus for CQ Cep, derived from our results is $(V_0 - M_V) = 12.0$, in excellent agreement with the value of 12.2 determined for the Cep OB1 association by Garmany & Stencel (1992). An evolutionary model involving case A mass-transfer and stellar-wind mass loss is probably required to explain the present state of this system.

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A ROSAT Survey of Wolf-Rayet Galaxies

I.R. Stevens[1] **and D.K. Strickland**[1]

[1] School of Physics and Astronomy, University of Birmingham, Birmingham, B15 2TT, UK

We present results from a ROSAT PSPC survey of the X-ray emission from Wolf-Rayet (WR) galaxies, a class of galaxies believed to be young starbursts (with ages of $t \sim 4 - 6$ Myr), many of which are blue compact dwarf galaxies. Of the 36 WR galaxies listed in the catalogue of Conti (1991), a total

of 14 have been observed deliberately or serendipitously with the ROSAT PSPC, and of these 7 have been detected.

The derived X-ray luminosities of WR galaxies range over nearly 3 orders of magnitude, from $L_x \sim 4 \times 10^{38}$ erg s^{-1} to 2×10^{41} erg s^{-1}. The X-ray spectra of the WR galaxies can typically be well fitted with a single temperature Raymond-Smith spectral model, with a temperature in the range of $kT = 0.3 - 1.0$ keV, with the general trend that the more X-ray luminous WR galaxies have hotter spectra. WR galaxies are significantly X-ray overluminous for their blue luminosity, compared to a sample of nearby spiral and starburst galaxies. In addition, the X-ray luminosity of WR galaxies correlates well with the far infrared luminosity L_{FIR}, and the number of Lyman continuum photons $N_{\rm Lyc}$. No strong correlation was found with the equivalent width of the WR emission feature around λ4686Å, the presence of which essentially defines the class of galaxies. There is little evidence of extended X-ray emission.

Various explanations for the observed properties of WR galaxies are explored, and we conclude that the X-ray emission provides strong evidence that a large fraction of the observed X-rays are coming from a hot superbubble formed by the combined action of stellar winds from massive early-type stars in the central starburst cluster. These results are consistent with and add weight to the view that WR galaxies are young starbursts, in which the duration of the star-forming epoch was very short, and that we are viewing them a few Myr after the initiation of the starburst. As such WR galaxies represent an important epoch in the evolution of starburst galaxies.

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Theoretical X-ray properties of colliding stellar winds in O+O star binaries

Julian M. Pittard and Ian R. Stevens

School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham B15 2TT

This is the first in a series of papers on colliding wind binaries which aim to present a detailed and quantitative comparison between theoretical models of colliding winds and X-ray observations. In this paper we concentrate on colliding stellar winds in O+O star binaries. We calculate the expected X-ray spectra and orbital lightcurves, and investigate the effect of different parameters (mass-loss rate, orbital separation, system inclination etc.) on the expected X-ray properties. In particular we investigate three model systems; one representing HD 165052 with equal winds, another representing HD 57060 with very unequal winds, and a third representing an intermediate case.

We demonstrate the sensitive relationship between system wind parameters and the shape of the X-ray lightcurve, and discuss these models in relation to recent *ROSAT* results on O+O star colliding wind systems. We find that the variation in X-ray luminosity during the orbit is primarily a result of varying extinction of the intrinsic X-ray luminosity by the more massive wind in the system. Secondary effects such as the intrinsic variation of the luminosity from instabilities in the shocked wind and variation with orbital separation are also quantified.

We also present the results of spectral fitting to our synthetic spectra. This is the first time that this method has been applied to colliding wind systems and promises to be an important future tool. Our theoretical results are intended primarily as examples but good agreement is found with observations.

We find that a Raymond-Smith (Raymond & Smith 1977) model's fitted to our simulations has a characteristic temperature of between 0.4–3.0 keV. This compares to typical observational results of $\sim$ 0.1–0.6 keV.

Future papers will sequentially add more physics into the theoretical models and comparisons with the latest observational results will be made. More detailed results for individual systems will follow in due course.

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Helium enhancements in luminous OB-type stars – the effect of microturbulence

N.D. McErlean[1], D.J. Lennon[2] and P.L. Dufton[1]

[1] The Department of Pure and Applied Physics, The Queen's University of Belfast, Belfast BT7 1NN, N. Ireland.

[2] Institut für Astronomie und Astrophysik der Universität München, Scheinerstrasse 1, D-81679 München 80, Germany.

We present non-LTE analyses of high quality spectra for two B-type supergiants, κ Orionis & ϵ Orionis (spectral types B0.5 Ia & B0 Ia respectively). We investigate the effect of including a microturbulent velocity in the H I, He II and He I line broadening on the derived stellar atmospheric parameters ($T_{\rm eff}$, $\log g$ and y). Its inclusion has a significant effect on the profiles of the lines of neutral helium and leads to approximately *normal* estimates for the helium fractional abundances for both supergiants. By contrast, adopting zero microturbulence implies significant helium overabundances, *if* we adopt the mean abundance of all the lines considered here. The He I lines at 4437, 4387 and 5047Å are found to be rather insensitive to microturbulence and hence are more reliable indicators of helium abundance. There are some remaining unresolved discrepancies, such as a systematic difference between singlet and triplet transitions which we attribute to the neglect of line blocking, while the 5015Å 2^1S – 3^1P transition remains much stronger than predicted. This latter problem we tentatively attribute to the neglect of sphericity; the generalized dilution effect discussed by Voels et al. (1989, ApJ, 340, 1073). We suggest that a judicious choice of He I lines, and the use of an appropriate microturbulent velocity, may contribute to resolving the 'helium discrepancy' in O-type stars. The question of the origin of a perceived microturbulence in supergiants is also briefly discussed in the context of stellar winds.

That two normal supergiants have close to solar helium abundances clearly implies that they have *not* undergone dredge-up in a previous red supergiant phase of evolution, supporting the contention that massive stars do not perform blue loops in the HR diagram at solar metallicity. Marginal evidence for a mild helium overabundance in κ Ori however could be interpreted as being due to mixing processes, perhaps during its main sequence lifetime.

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A colliding wind model for the Wolf-Rayet system HD 152270 (WR 79)

Siegfried Lührs[1]

[1] Astronomisches Institut, Westfälische Wilhelms-Universität
Wilhelm-Klemm-Str. 10, D-48149 Münster, F.R. Germany
e-mail:100327.2626@compuserve.com

New orbital elements for the binary system HD 152270 (WC7 + O6) are derived from high resolution observations and literature data, obtained between 1944 to 1989. Variations in position and structure of the peak profile, overlying the flat-topped C Roman3 569.59 nm line, are used to derive a colliding wind model (cone model) for the system. The model is used to construct synthetic line profiles which are compared with the observed profiles.

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Coupled mass and angular momentum loss of massive main sequence stars

N. Langer

Institut für Theoretische Physik und Astrophysik, Universität Potsdam, D–14415 Potsdam, Germany

We investigate the interaction of mass loss and rotation during core hydrogen burning in massive stars. We compute their main sequence evolution assuming rigid rotation, and carry angular momentum as a passive quantity in the stellar interior but incorporate its effect on the stellar mass loss rate. We consider the example of a $60 M_\odot$ star assuming various initial rotation rates.

We show that rotation may substantially enhance the total main sequence mass loss of massive stars. Furthermore, we argue that the surface layers of rotating massive main sequence stars may reach the limit of hydrostatic stability ("Ω-limit") by achieving a considerable fraction of their Eddington luminosity. We show that this process is not catastrophic for the star, but rather that the coupling of mass and angular momentum loss limits the mass loss rate $\dot{M}_\Omega$ of main sequence stars at the Ω-limit. $\dot{M}_\Omega$ is determined through the angular momentum loss imposed by the Ω-limit rather than by atomic physics. For our $60 M_\odot$ sequences, it is $\dot{M}_\Omega \simeq 10^{-5} M_\odot\, yr^{-1}$.

We find a convergence of the rotational velocities of main sequence stars of a given initial mass at the Ω-limit, but a strong dependance of their mass at core hydrogen exhaustion from the *initial* rotation rate. Since then also the post-main sequence evolution depends on the initial amount of angular momentum, we argue that this is a third independent initial parameter for the evolution of massive stars, as important as initial mass and metallicity.

We briefly discuss observable consequences of the coupling of mass and angular momentum loss, e.g. a significant decline of the projected rotational velocity $v \sin i$ towards the cool end of the main sequence, a period of strongly enhanced and aspherical mass loss, disks or rings in the equatorial plane of the star reminiscent of B[e]-stars, and highly bipolar circumstellar structures.

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Detection of WR stars in the metal–poor starburst galaxy IZw 18

F. Legrand[1] , D. Kunth[1] , J.-R. Roy[2] , J.M. Mas-Hesse[3] and J.R. Walsh[4]

[1] Institut d'Astrophysique de Paris, CNRS, 98bis boulevard Arago, F-75014 Paris, France.

[2] Département de physique and Observatoire du mont Mégantic, Université Laval, Québec Qc G1K 7P4

[3] LAEFF, Apdo 50727, E-28080 Madrid, Spain.

[4] European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching, Germany

Wolf-Rayet stars (WR) have been detected in the NW region of the metal–poor starburst galaxy IZw 18. The integrated luminosity and FWHM of the bumps at 4650 Å and 5808 Å are consistent with the presence of a few individual stars of WC4 or WC5 type. Evolutionary synthesis models predict few WRs in this galaxy, but only of WN type. The presence of WC stars at such low metallicity could however be explained by high mass loss rates, which would constrain the IMF upper mass cut-off in IZw 18 to be higher than 80 $M_\odot$ or alternatively favor a binary channel for WR formation. WC stars could also explain the strong and narrow HeII 4686Å emission line which peaks co–spatially with the WR bump emission, as suggested by Schaerer (1996). This detection shows that WR stars, even of WC type, are formed at metallicities below 1/40th solar.

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Submitted Papers

The effect of rotation on the absolute visual magnitudes of OB stars measured with Hipparcos

H.J.G.L.M. Lamers[1,2], J.M.A.G. Harzevoort[1,2], H. Schrijver[2]

, **R. Hoogerwerf[3] and R.P. Kudritzki[4,5]** [1]

Astronomical Institute, University of Utrecht, Princetonplein 5, NL-3584 CC, Utrecht, The Netherlands

[2] SRON Laboratory for Space Research, Sorbonnelaan 2, NL-3584 CA, Utrecht, The Netherlands

[3] Leiden Observatory, PO Box 9513, NL-2300 RA, Leiden, The Netherlands [4] Institut for Astronomie und Astrophysik der Universität München, Scheinerstrasse 1, 81679 München, Germany

[5] Max Planck Institut für Astrophysik, Karl-Schwarzschild-Str.1, 85740 Garching bei München, Germany

We derive the absolute visual magnitudes of 14 OB-stars of luminosity class III to V from the parallaxes measured by Hipparcos. The values of M_V can differ by as much as $1.^m5$ from the M_V-spectral type calibration. Slowly rotating stars, $v \sin i < 100$ km s^{-1}, are significantly fainter in M_V than stars with $v \sin i > 100$ km s^{-1} *of the same spectral type* by about 1 magnitude. We discuss this effect and argue that it is due to the influence of rotation on the assignment of spectral types and luminosity class. Slowly rotating stars are also fainter than the standard M_V-spectral type relation. This effect has important consequences on the distance determinations of stars and clusters from M_v and V.

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In Proceedings

V 439 Cyg, the Red Star That Became Blue

V.F. Polcaro [1] **and L. Norci**[2]

[1] Istituto di Astrofisica Spaziale, CNR
Frascati RM, Italy
[2] Dunsink Observatory, Dublin Institute for Advanced Studies
Dublin, Ireland

Most of the peculiar open cluster Berkeley 87 members are young, heavily reddened OB stars, but a few are much more evolved objects, as the WO star Sand 5 and the M3.5I variable BC Cyg. This evidence makes the evolutionary status of the cluster extremely uncertain. Berkeley 87 is probably part of the star forming region ON2, where many compact H II regions, strong OH masers and CO and ammonia molecular clouds have been detected. Two strong IRAS sources, one of that coincident with BC Cyg and the other near to the apparent cluster center, and a diffuse far- infrared emission are present in the cluster.

The cluster member n.15 in the Turner and Forbes (PASP, 1982) list is an emission line star also known as V 439 Cyg and MWC 1015. This star drammatically changed its spectrum from late to an early type in a few decades. Furthermore, some absorption lines that were still present in 1987 disappeared completely since 1988. The star is characterized by a strong IR excess and a peculiar position in the HR diagram. We present new spectroscopic data on this unique object and suggest a possible explanation of its spectral change: it is actually conceivable that a star with $M_{\rm initial} \simeq 40 M_{\odot}$ will have a quite short period during its evolution when it behaves as a sort of weak LBV or as a extraordinary short living RSG or a combination of both. We could therefore think of V 439 Cyg as a RSG/LBV.

Demonstrating that V 439 Cyg is actually in a RSG/LBV evolutionary stage could prove a very powerful test of high mass stars evolutionary models. The upper limit to the cluster age of 4 My derived from the CM diagram of the OB stars and the lower limit of 3.5 My deduced by the presence of a WO star, would constrain the age at which the instability RSG/LBV is reached. This would provide a fixed point to which the evolutionary models can be anchored.

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